Navy Experimental Diving Unit
321 Bullfinch Rd.
Panama City, FL 32407-7015

TA 01-19
NEDU TR 02-15
November 2002

EXERCISE HEART RATE AS A PREDICTOR OF OXYGEN CONSUMPTION DURING DECOMPRESSION FROM SATURATION DIVING

NAVSEA
NAVAL SEA SYSTEMS COMMAND
Navy Experimental Diving Unit

Authors: Barbara E. Shykoff, Ph.D.
Marie E. Knafelc, CAPT, MC, USN

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited
2b. DECLASSIFICATION/DOWNGRADING AUTHORITY	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NEDU Technical Report No. 02-15	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Navy Experimental Diving Unit 6b. OFFICE SYMBOL (If Applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) 321 Bullfinch Road, Panama City, FL 32407-7015	7b. ADDRESS (City, State, and Zip Code)
8a. NAME OF FUNDING SPONSORING ORGANIZATION Naval Sea Systems Command 8b. OFFICE SYMBOL (If Applicable) 00C	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) 2531 Jefferson Davis Highway, Arlington, VA 22242-5160	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. | PROJECT NO. | TASK NO. 01-19 | WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
(U) **EXERCISE HEART RATE AS A PREDICTOR OF OXYGEN CONSUMPTION DURING DECOMPRESSION FROM SATURATION DIVING**

12. PERSONAL AUTHOR(S)
Barbara E. Shykoff, Ph.D., Marie E. Knafelc, CAPT, MC, USN

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical Report	Mar 2001 — Apr 2001	November 2002	24

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
ergometer work, underwater exercise, oxygen consumption measurements

19. ABSTRACT (Continue on reverse if necessary and identify by block number) Please see 2nd page.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT
[ ] UNCLASSIFIED/UNLIMITED [X] SAME AS RPT. [ ] DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
NEDU Librarian	850-230-3100	

DD Form 1473

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

The correlation between heart rate and oxygen consumption has been questioned during submerged exercise or exercise under pressure. We studied the relationships of heart rate to oxygen consumption ($\dot{V}O_2$) and of $\dot{V}O_2$ to ergometer setting in eight divers during decompression from a saturation dive in a helium-oxygen atmosphere. Measurements were made at 300, 190, 66, and 33 feet of seawater (1019, 682, 303, 202 kPa (a)). $\dot{V}O_2$ during submerged exercise (maximum 75 W) was calculated from the MK 16 underwater breathing apparatus (UBA) bottle pressure drop, and during dry exercise (up to 75% of maximum $\dot{V}O_2$) by expired gas collection. $\dot{V}O_2$ increased linearly with ergometer work with the same slope submerged or dry, but the no-load intercept was higher submerged than dry. The work of moving the water and of breathing on the UBA corresponded to 54 W ± 15 W. Heart rate increased linearly with $\dot{V}O_2$. The slope was independent of depth or immersion, and the intercept was independent of depth. The median error in estimating $\dot{V}O_2$ from heart rate was 12% on the surface, 23% submerged, and 31% in the dry chamber. Heart rate was not a good predictor of $\dot{V}O_2$ during dry or submerged exercise in the hyperbaric chamber.

ACKNOWLEDGMENTS

We are indebted to many for the successful completion of this study. Mr. Jack Schmitt provided us the opportunity to run our tests during the dive. The divers cheerfully and conscientiously performed the study from "the inside." Mr. Henry Boone and the instrumentation team made the data acquisition possible. HM1 Susan Mayberry and LT Lincoln Wills assisted with the maximum oxygen consumption measurements. Medical deck teams directed the experiment and acquired our data, while control room personnel drove the chamber and took care of overall diver safety. Others managed the necessary facilities and creature comforts for the divers. We thank them all.

CONTENTS

INTRODUCTION

Under normobaric and normothermic conditions, heart rate rises in direct proportion to the rate of oxygen consumption during exercise.[1–6] Even across subjects of very different fitness levels, nearly the same relationship holds between heart rate and the fraction of the individual's maximum oxygen consumption.[3,4,6] The same linear relationship has been reported for swimming as for running.[2] Exercise heart rate sometimes is used as a surrogate for oxygen consumption[4]. However, some published data[1] and anecdotal evidence at the Navy Experimental Diving Unit (NEDU) have suggested that during exercise under pressure or under water while using underwater breathing apparatus (UBA), heart rate might not be a good predictor of oxygen consumption, or that it might be nearly independent of external workload.

This study was conducted to investigate the relationship between heart rate and oxygen consumption during exercise in comfortably cool air and water at different pressures (depths) and to estimate the utility of heart rate as an estimator for oxygen consumption during use of the MK 16 UBA. We hypothesized that the linear relationship between oxygen uptake and heart rate during exercise would be independent of surrounding pressure whether the subjects exercised in air or in water, though the initial (resting) heart rates might differ.

METHODS

GENERAL

Exercise studies were performed before compression and during the decompression phase of a saturation dive to 350 feet of seawater (fsw) (1172 kPa) in the Ocean Simulation Facility at NEDU. Eight male divers spent twelve days in the hyperbaric chamber, where they breathed a mixture of helium and oxygen with a nominal oxygen partial pressure of 0.44 atmospheres absolute (ATA) (0.45 kPa(a)). Measurements were made during two-day periods at pressures of 300, 190, 66, and 33 fsw (1019, 682, 303, and 202 kPa(a)) during the decompression phase: the first day with subjects using two electrically braked submerged cycle ergometers (Warren Collins; Braintree, MA) in the wet chamber, and the second day with subjects using one upright cycle ergometer in the dry chamber. The protocol had been approved by the Committee for Protection of Human Subjects at NEDU, and divers had given written informed consent.

EXPERIMENTAL DESIGN AND ANALYSIS

We determined maximum aerobic capacity at sea level before the dive and then measured both oxygen consumption and heart rate at different bicycle ergometer settings during the dive. Three exercise intensities were used for each diver during submerged exercise, and four during dry exercise. All eight divers participated.

Separate linear regression equations for oxygen consumption against heart rate were calculated for each diver for data from submerged and dry exercise at each depth. Regression equations for each diver, wet or dry, with all depths pooled, also were calculated. Oxygen consumption, the variable with more experimental error, was treated as the dependent variable in the linear regression. As the physiologically dependent variable is heart rate, the equations were transformed. Fraction of the variance explained by the regression does not change when one swaps dependent and independent variables. Stepwise forward regression was used with both the square of heart rate and the reciprocal of heart rate as potential independent variables.

A two-way analysis of variance was used to test the hypothesis that there is no effect of pressure or of submerged vs. dry exercise on the slopes or the intercepts. Significance was accepted at the 95% confidence level.

EQUIPMENT AND INSTRUMENTATION

The Collins CPX cardiopulmonary monitoring system (Warren Collins; Braintree, MA) was used to control the ergometer and to measure oxygen consumption on a breath-by-breath basis during the testing of maximum aerobic capacity. A Collins ergometer control unit also was used to control the ergometers in the chamber. ECG was recorded with a telemetry unit (Q-tel Rehab, Quinton Instrument Company; Seattle, WA).

Dry oxygen consumption was measured by collecting expired gas. The subject wore nose clips and breathed through a mouthpiece connected to a system of one-way valves. A meteorological balloon (nominal capacity 168 L, Kaysam Worldwide Inc.; Totowa, NJ) was attached to the expiratory port with a three-way stopcock. To measure the expired fractions of oxygen and carbon dioxide, a calibrated mass spectrometer (MGA 1100, Marquette Medical; Milwaukee, WI) was used. Another mass spectrometer was used to sample gas composition from the mouthpiece. Heart rate was counted from a three-lead ECG signal and blood pressure was measured by manual sphygmomanometry during the first minute at each exercise level.

Submerged oxygen consumption was calculated from the decrease in oxygen supply pressure in the closed-circuit UBA. Subjects used the MK 16 MOD 0 UBA, which adds oxygen to the breathing circuit to maintain the partial pressure of oxygen at 76 kPa (0.75 ATA).[7] The gas used for purging the mask and making up volume was a depth-specific helium-oxygen mixture with an oxygen partial pressure of 65 kPa to 80 kPa (0.65 to 0.8 ATA) to match the 75 kPa control oxygen partial pressure for the rig. Thus, in general, the volume of oxygen lost to leaks was replenished independently of the oxygen bottle supply, and drops in oxygen bottle pressure represented oxygen consumed by the diver.

Oxygen bottle pressure was recorded automatically with a pressure resolution of ± 34 Kpa (± 5 PSI) (Druck; New Fairfield, CT) every 30 seconds with a computerized data acquisition system and a program written in Labview (National Instruments; Austin, TX).

PROCEDURES

Maximum Aerobic Capacity

Each diver's aerobic capacity was assessed in the laboratory at sea level pressure one week before the divers entered the chamber. The rate of bicycle ergometer work was increased from 0 W to 200 W in 50-watt steps of two-minute duration and then in 25-watt increments to exhaustion. Oxygen consumption was measured both on a breath-by-breath basis and by collecting expired gas at each exercise rate greater than or equal to 200 W. After the end of exercise, the gas composition and volumes were measured by emptying the balloons through a gas meter and a calibrated mass spectrometer. Heart rate and blood pressure were recorded during the first minute at each exercise level.

Wet Exercise Testing

During wet exercise testing, two divers exercised simultaneously while a third served as a safety diver. Every 30 seconds, telemetered heart rate was entered manually into the computer file, where the oxygen supply pressure was recorded automatically. Water temperature was 78±1 °F (25.6±0.8 °C), and subjects wore dive skins.

Each diver pedaled at three ergometer settings: freewheeling, either 35 W or 50 W, and either 60 W or 75 W. The loads for the individual divers were selected to give a moderate range of oxygen consumption during a trial run in the water. The total work rate while pedaling in the water is measurably greater than the ergometer setting because of the added work done to move water and to flex the diver's suit.[5,8] Subjects worked at the lower two rates for 20 minutes and at the highest rate for 15 minutes. The sustained work period was needed for adequate resolution of the oxygen supply pressure drop.

Dry Exercise Testing

During dry exercise testing, one diver served as a subject while others assisted. Four ergometer loads were applied: loadless pedaling, then 30%, 50%, and 75% of the watt load at which maximum aerobic capacity had been attained for that subject during the predive measurement.

Subjects were considered to be in a steady state of oxygen consumption either when heart rate was constant for two minutes or when five minutes had elapsed at a workload, whichever occurred first. Once steady state was reached at an exercise level, a tender directed expired gas into the balloon by turning the valve at end expiration. Gas was collected for approximately 60 seconds, after which the bag was closed by turning the stopcock. The precise duration of the gas collection was recorded.

Blood pressure was measured as a diver safety check during the first minute of exercise. Heart rate was recorded manually during the collection of the gas.

After a subject completed his final exercise level, a person in the chamber emptied the bags one at a time through a gas meter with a mass spectrometer probe on its inlet. The composition, volume, and temperature of the mixed expired gas were recorded on paper for each exercise level, along with general chamber gas composition and temperature. The inspired gas composition was recorded from the mouthpiece.

Data Analysis — Oxygen Consumption

Submerged

Oxygen consumption ($\dot{V}O_2$) by submerged divers was calculated from the rate of change in oxygen bottle pressure by rearranging the ideal gas law:

$$\dot{V}O_2 \text{ (L/min STPD)} = ((\Delta P/\Delta t) /101.3) \cdot V_b \cdot (273 / T_w),$$

where $\Delta P/\Delta t$ = average rate of oxygen pressure drop (kPa/min), V_b = oxygen supply bottle volume (L), T_w = water temperature (K), and STPD signifies standard temperature and pressure dry — that is, 0 °C = 273 K and 101.3 kPa, without water vapor. The measured bottle volume was 2.8 L.

Data from the first five minutes at the two lower work rates and from the first two minutes for the highest workload were discounted in oxygen consumption calculations. These periods were allotted for subjects to attain steady-state oxygen consumption at the new work rates and for thermal equilibration of the rig at the start of the experiment. Calculations thus could be performed over a maximum of 15 minutes for the two lower work rates and a maximum of 13 minutes at the highest work rate. When bottle pressure decreased in a stair-step form from one UBA oxygen add valve opening to the next, the pressure decrease was calculated from just before one pressure step (valve opening) to just before the last pressure step available in the record. Rate of pressure drop was the pressure difference divided by the time between measurements. We chose the end of the pressure plateaus, the latest possible times after gas discharges, to minimize the pressure artifact caused by expansion cooling. However, when oxygen was added frequently enough to obscure the steps, linear regression on all points between the two times was used. The average oxygen consumption over about 12 to 15 minutes of exercise was obtained at each workload.

Dry

Oxygen consumption during dry exercise was calculated from the volume expired, the composition of the expired gas, and the composition of the inspired gas using the standard approach described below.

The amount of oxygen consumed is the amount of oxygen inhaled minus the amount of oxygen exhaled. The amount of oxygen exhaled is the total gas volume expired, converted to STPD, and multiplied by the fraction of oxygen in the bag. To convert this amount to STPD, one applies the ideal gas law and assumes that the exhaled gas is saturated with water vapor at the temperature measured. The amount of oxygen inhaled is the total volume inhaled, converted to STPD, and multiplied by the fraction of oxygen in the inhaled gas.

Inhaled and exhaled volumes differ because of gas exchange and changes in water vapor content, and only exhaled volume is collected. However, the volumes of inert gas inhaled and exhaled during the one-minute gas collection can be assumed to be equal. Thus, the volume of gas inhaled is the volume exhaled multiplied by the ratio of the inert fraction exhaled to that inhaled, the Haldane correction. Since the fraction of inert gas is the complement of the fractions of oxygen and carbon dioxide, volume inhaled can be expressed in terms of the measured quantities:

$$\dot{V}O_2 = (V_E/\text{time}) \cdot (F_IO_2 \cdot ((1 - F_EO_2 - F_ECO_2)/(1 - F_IO_2 - F_ICO_2)) - F_EO_2),$$

where V_E is the bag volume collected (STPD); time is the duration of the gas collection; F_IO_2 and F_EO_2 are the fractions of oxygen in the inspired and expired gas, respectively; and F_ICO_2 and F_ECO_2 are the fractions of carbon dioxide in the inspired and expired gas, respectively. The fractions are those for dry gas.

RESULTS

Diver characteristics, including maximum oxygen consumption, are given in Table 1.

Surface oxygen consumption measurements for the breath-by-breath system correlated with the bag measurements, with a regression coefficient of 0.82. The surface data presented are from the breath-by-breath system, averaged over the second minute at each workload.

A straight-line regression relationship between heart rate and oxygen consumption was significant for submerged and dry exercise for each subject at each depth. The average regression parameters for each depth are presented in Table 2. Repeated measures analysis of variance showed no effects of depth on the regression slopes and intercepts of heart rate against oxygen consumption.

With all depths pooled, heart rate also varied linearly with absolute oxygen consumption for each subject (Fig. 1); neither higher-order nor reciprocal terms entered the regression fits. Slopes did not differ among submerged exercise, dry exercise at depth, or dry exercise on the surface. The intercepts were significantly different ($p<0.001$), with the intercept for dry exercise in the chamber lower than that for surface exercise, and that for submerged exercise in the chamber lower still (Table 2). However, the regression uncertainty of the intercepts was such that the ranges overlapped (Table 2).

The median and range of standard errors of the regression estimates of oxygen consumption as a function of heart rate were 12% (9% to 23%) on the surface, 23% (14% to 45%) submerged, and 31% (13% to 40%) during dry exercise in the hyperbaric chamber.

The accuracy of measurement of the pressure differences used to compute submerged oxygen consumption ranged from ±30% at the lowest oxygen consumption to ±8% at the highest, as calculated from transducer accuracy and the pressure differences recorded.

The relation of oxygen consumption to ergometer work was well-described by a straight-line relationship, which was the best polynomial fit (Table 3). The slopes of the relation did not differ among subjects, among depths, or among the locations surface, dry chamber with HeO_2, or submerged at depth. The average slopes were $(1.1 \pm 0.2) \times 10^{-2}$ L/min/W submerged, $(1.1 \pm 0.1) \times 10^{-2}$ L/min/W dry under pressure, and $(9.2 \pm 0.2) \times 10^{-3}$ L/min/W on the surface. The intercepts differed among subjects under all conditions ($p<0.01$), and across depths for submerged exercise, with that at 300 fsw higher than that at any other depth ($p<0.02$). The average intercept for dry exercise was half of that for submerged exercise ($p<0.001$). Loadless pedaling represented an average oxygen consumption of 0.67 ± 0.03 L/min at the surface, 0.63± 0.07 L/min dry at pressure and 1.2 ± 0.1 L/min submerged.

The extra work in the water added an average 0.6 ± 0.2 L/min to the oxygen consumption of cycling exercise, a rate that corresponds to about 54 ± 15 W of external work. The extra work of cycling in the water while breathing from the MK 16 was closer to 73 W at 300 fsw, and 49 W at the shallower depths.

DISCUSSION

The increase of heart rate with increasing oxygen consumption was not affected by differences in ambient pressure, by the presence of helium instead of nitrogen, or by submersion. However, the ability to predict oxygen consumption from heart rate, already somewhat imprecise at the surface, was compromised in the hyperbaric chamber or by submersion. While the physiological link between the heart rate and oxygen consumption was preserved, other factors influenced heart rate and made it a poor surrogate measure for the intensity of work done.

Although the confidence intervals of the intercepts for the three conditions overlapped (Table 2), the intercepts were lower under pressure than at the surface, and lower in the water than in the dry chamber. Heart rates therefore were lower under pressure at any level of oxygen consumption, because the slopes were not different among conditions.

The lower heart rate was probably a combination of hyperoxic bradycardia [9-12] and bradycardia in response to breathing helium.[13] The progressively lower heart rate intercepts for surface exercise in air, for dry exercise at an oxygen partial pressure of 0.45 kPa, and for submerged exercise at an oxygen partial pressure of 0.76 kPa, are probably an oxygen dose response,[9] although not all investigators have seen one.[14] Hyperbaric bradycardia has been postulated to be pressure dependent,[10] but we saw no effect of pressure, in agreement with other investigators.[9,11,12] We may have missed a pressure effect on heart rate by measuring only during the decompression phase of the dive; hyperbaric bradycardia has been reported to be transient.[15] The density at 300 fsw with a helium-oxygen mixture is equivalent to that of atmospheric air, but gas density has been shown unimportant in the bradycardic response.[9,10] The diving response to water on the face is unlikely here, as the divers wore full face masks when submerged.

Measurement error, a non-biologic source of variation, differed between submerged and dry calculations. The important error sources in the submerged measurements were the estimation of the rate of pressure drop and the 0.5-minute time resolution. The potential sources of errors for dry oxygen consumption measurements were gas composition uncertainty from either the bag or chamber, bag volume measurement error, collection time error, and undetected leaks in the weather balloons.

Visual inspection showed that lines joining the first oxygen pressure used in submerged calculations to the ones 12- to 15-minutes later touched nearly all of the intermediate plateau pressures. As a test of three oxygen consumption measurements, all plateau points before the oxygen valve opened were selected; the linear regressions explained more than 99% of the variation in the values, the standard error of the slopes was less than 3%, and the slopes differed by less than 3% from the piecewise slopes between the first and the last plateau points. A piecewise calculation was used for all other stepwise pressure drops, with an assumed 3% measurement error in the difference. This uncertainty adds to the 8% to 30% uncertainty caused by the pressure transducer resolution. The 30-second time resolution yields a possible error of half a minute out of 12 to 15 minutes, less than 5%. Together, this gave a resolution of ±38.5% for submerged oxygen consumption at low workloads and of ±16.5% at higher workloads.

Expired gases for dry oxygen consumption calculations were sampled using the mass spectrometer while a diver squeezed the gas out of a weather balloon and through the gas meter. The mass spectrometer resolution was ±0.5 on the last digit of the display. Inspired gas was sampled from the mouthpiece using a mass spectrometer during inspiration. The resolution for bag volume ranged from 0.1% to 1% of the gas volume. The uncertainty in time measurement was less than 2%. Thus, total measurement uncertainty for dry oxygen consumption was less than 5% in the absence of bag leaks.

The heart rates recorded were the averages of at least six readings. Although there was more electrical interference in the ECG signal from the water than from the dry chamber, the greater noise contamination of submerged ECG was balanced by the longer time over which to obtain heart rate. The heart rate precision was ± 0.5 beats/minute, but at the heaviest exercise with noise was closer to ± 5% for single readings.

The measurement errors help to explain uncertainties in slope of the heart rate, oxygen consumption relation (Table 2) and of the slopes of oxygen consumption to ergometer workload (Table 3). However, other factors seem to have influenced heart rate for at least some subjects, as shown by the deviation of data from the regression lines (Fig. 1).

The non-metabolic factors driving heart rate appear to have differed among subjects and with depth. Some aspect of the breathing gear is an obvious suspect, particularly as one subject had had much lower heart rates while practicing the protocol with a different UBA. That diver (subject 6) told us that he could not exhale fully with the MK 16. Thus, heart rate for some subjects might have been increased in response to high lung volume resulting from the high expiratory elastic load of the UBA or in response to elevated breathing frequencies used to compensate for small tidal volumes from the UBA. Other possible factors leading to elevated heart rate include mental stress,[16] caffeine consumption prior to exercise, fatigue, or response to carbon dioxide if scrubbing in the UBA was inadequate. Because the UBAs were maintained following standard Navy diving practice,[7] carbon dioxide scrubbing should not have been an issue.

The submerged ergometers had the same calibration characteristics as the dry ergometer, as shown by the lack of difference in the slopes of the relation between ergometer setting and oxygen consumption between dry and submerged exercise (Table 3, Fig. 2). As others also have found,[14] the conditions in the dry hyperbaric chamber did not alter the mechanical efficiency of cycling, as shown by the lack of difference in the regression parameters with depth. However, the different intercepts for dry and submerged exercise represent a constant additional energy requirement during submerged exercise. Variability of the intercepts of the linear regression was greater during wet exercise when the UBA was in use than during dry exercise. The submerged intercept was highest at 300 fsw (Fig. 3b, Table 4), an indication that some subjects had a non-exercise load that was greatest at the first test depth. The no-load oxygen consumption may have decreased at shallower depths in part because the divers became more familiar with the equipment as the dive continued. Although the work of breathing for the MK 16 is greater at 300 fsw than at shallower depths because of greater gas density, the maximum sustainable respiratory work rate is 4 W,[17] while the maximum short-term rate, seen during peak exercise, is 8 W[18] to 13 W.[19]

The average additional 54 W in the water is greater than the 25 W reported by Thalmann et al. for divers using surface-supplied air[5] and closer to the 50 W reported by Knafelc et al. for minimally dressed divers breathing with the MK 15.[8] The discrepancy is too high to have been caused by the higher work of breathing with the closed-circuit UBA, as noted above.[17-19] The difference may be caused by different arrangements of equipment in the two laboratories involved; the lower work rate was measured using one cycle ergometer in a small, completely water-filled chamber, while the larger work rate was seen with two ergometers side by side in a large chamber with an air-water interface. The interaction of the water currents established by the two ergometers and the energy needed to lift waves against gravity may have increased the work of cycling.

During dry and submerged cycling at depths down to 300 fsw, a linear relationship between oxygen uptake and heart rate during exercise was seen, independent of surrounding pressure or the use of a helium-oxygen breathing gas instead of air, although the intercept was shifted. The regression equations usually explained most of the variance on a per subject basis, although in four subjects, less than 70% of the variance in submerged heart rate was explained by oxygen consumption (Table 4). However, the use of heart rate as a surrogate for oxygen consumption is ill-advised. Even for surface measurements, other authors have reported a range in error from –11% to +5%,[20] or coefficients of variation from 11% to 20%.[21] Our coefficients of variation for surface measurements were determined for the same data from which the predictive equations were calculated, which increased the apparent precision. The large coefficients of variation at depth, dry or submerged, made the estimated oxygen consumption too unreliable to be useful, even with a surface "calibration" curve for an individual diver (Table 4).

Any attempt to use group data to predict for the individual is even worse. Figure 3 shows the data, normalized by each subject's maximum oxygen consumption as determined by collection of expired gas. A very wide band of percentages of maximum oxygen consumption corresponds to a single heart rate. Furthermore, an estimate based on the surface regression line for this population provides a very poor estimate of percentage of maximal oxygen consumption for the same divers submerged and breathing with the MK 16 UBA.

CONCLUSIONS

During dry cycling at depths down to 300 fsw, the linear relationship between oxygen uptake and heart rate during exercise was preserved, independent of surrounding pressure or the use of a helium-oxygen breathing gas instead of air. No additional work of breathing was measurable with the helium atmosphere at these depths. Nearly all of the increase in oxygen consumption could be explained by increases in ergometer work, and the median of the variance in heart rate explained by oxygen consumption was 86%. However, the median coefficient of variation for estimation of oxygen consumption for an individual subject using his own surface relationship was 27%, with a range from 18% to 59%.

During submerged cycling at depths down to 300 fsw, while the linear relation was preserved, independent of surrounding pressure, the variability in the relationship was large. Most of the increase in oxygen consumption could be explained by increases in ergometer work, with a depth-specific fixed extra work rate for exercise in the water. However, the median of the variance in heart rate explained by oxygen consumption was only 68%, and the median coefficient of variation for estimation of oxygen consumption for an individual using his own surface dry relationship was 39%, with a range from 24% to 73%. Although the relation between heart rate and oxygen consumption is present, additional factors make heart rate a poor indicator of oxygen consumption during submerged exercise using the MK 16 UBA.

REFERENCES

1. J. Dwyer, "Estimation of Oxygen Uptake from Heart Rate Response to Undersea Work," *Undersea Biomed. R.*, Vol. 10, No. 2 (June 1983), pp. 77–87.
2. C. Hauber, R. L. Sharp, and W. D. Franke, "Heart Rate Response to Submaximal and Maximal Workloads during Running and Swimming," *Int. J. Sports Med.,* Vol. 18, (1997), pp. 347–353
3. L. B. Rowell, *Human Circulation: Regulation during Physical Stress* (New York: Oxford University Press, 1986).
4. American College of Sports Medicine; B. A. Franklin, W. H. Whaley, and E. T. Howley, eds., *ACSM's Guidelines for Exercise Testing and Prescription,*6th ed. (Philadelphia, PA: Lippincott, Williams and Wilkins, 2000).
5. E. D. Thalmann, D. K. Sponholtz, and C. E. G. Lundgren, "Effects Of Immersion and Static Lung Loading on Submerged Exercise at Depth," *Undersea Biomed. R.* , Vol. 6, No. 3 (Sept 1979), pp. 259–290.
6. H. L. Taylor , Y. Wang, L. Rowell, and G. Blomqvist, "The Standardization and Interpretation of Submaximal and Maximal Tests of Working Capacity," *Pediatrics*, Vol. 32, (1963), pp. 703–722.
7. U.S. Navy Dive Manual, revision 4, 20 Jan. 1999, Ch.17.
8. M. Knafelc, *Oxygen Consumption Rates for Divers in Various Thermal Garments,* Navy Experimental Diving Unit (unpublished data). Test Plan 86/33; Oxygen consumption series (Nov 1986).
9. Lin, YC, and E.N. Kato, "Effects of Helium Gas on Heart Rate and Oxygen Consumption in Unanesthetized Rats,"*Undersea Biomed. R.*, Vol 1, No. 3 (Sept 1974), pp. 281–290.
10. Shida, K.K. and Y.C. Lin, "Contribution of Environmental Factors to the Development of Hyperbaric Bradycardia,". J. *Appl. Physiol.* Vol. 50 No. 4 (1981), pp. 731-735.
11. Linnarsson, D., A.Östlund, F. Lind, C.M. Hesser, "Hyperbaric Bradycardia and Hypoventilation in Exercising Men: Effects of Ambient Pressure and Breathing Gas," *J. Appl. Physiol.* Vol. 87, No. 4 (1999), pp. 1428-1432.
12. Bradley, M.E., N.R.Anthonisen, J. Vorosmarti, P.G. Linaweaver, "Respiratory and Cardiac Responses to Exercise in Subjects Breathing Helium-Oxygen Mixtures at Pressures from Sea Level to 19.2 Atmospheres," In: *Underwater Physiology. Proceedings of the Fourth Symposium on Underwater Physiology* (1976), edited by C.J. Lambersten. Bethesda, MD: Fed. Am. Soc. Exp. Biol., pp. 617-626.
13. Salzano, J., E.M. Overfield, D.C. Rausch, H.A. Saltzman, J.A. Kylstra, J.S. Kelley, and J.K. Summitt, "Arterial Blood Gases, Heart Rate, and Gas Exchange during Rest and Exercise in Men Saturated at a Simulated Seawater Depth of 1000 Feet," IN: *Underwater Physiology, Proceedings of the Fourth Symposium on Underwater Physiology,* New York (1971), Academic Press, pp. 347-356.

14. Dressendorfer, R.H., S.K. Hong, J.F. Morlock, J. Pegg, B. Respicio, R.M. Smith, and C. Yelverton, "Hana Kai II: A 17-Day Dry Saturation Dive at 18.6 ATA. V. Maximal Oxygen Uptake," *Undersea Biomed. R.* Vol. 4, No. 3, (Sept 1977), pp. 283-296.
15. Smith, R.M., S.K. Hong, R.H. Dressendorfer, H.J. Dwyer, E. Hayashi, and C.Yelverton, "Hana Kai II: A 17-Day Dry Saturation Dive at 18.6 ATA. IV. Cardiopulmonary Functions." *Undersea Biomed. R.* Vol. 4, No. 3, (Sept 1977), pp. 267-281.
16. A. Szabo, F. Peronnet, L. Gauvin, and J. J. Furedy, "Mental Challenge Elicits 'Additional' Increases in Heart Rate during Low and Moderate Intensity Cycling," *International J. of Psychophysiol*, Vol. 17, No. 3 (Aug 1994), pp. 197–204.
17. Warkander, D.E. and C.E.G. Lundgren, "Development of Comprehensive Performance Standards for Underwater Breathing Apparatus." Final report. Center for Research and Education in Special Environments, University at Buffalo, Buffalo, NY (2000), p B4
18. Hesser, C.M., D. Linnarsson, and L. Fagraeus, "Pulmonary Mechanics and the Work of Breathing at Maximal Ventilation and Raised Air Pressure," *J. Appl. Physiol.* Vol. 50, No. 4 (1981), pp. 747-753.
19. Milic-Emili, J. and M.M. Orzalesi, "Mechanical Work of Breathing during Maximal Voluntary Ventilation," *J. Appl. Physiol.* Vol 85, No. 1 (1998), pp. 254-258.
20. Moon, J.K. and N.F. Butte, "Combined Heart Rate and Activity Improve Estimates of Oxygen Consumption and Carbon Dioxide Production Rates," *J. Appl. Physiol.* Vol. 81, No. 4 (1996), pp. 1754-1761.
21. Li, R., P. Deurenberg, and J.G. Hautvast, JG, "A Critical Evaluation of Heart Rate Monitoring to Assess Energy Expenditure in Individuals," *Amer. J. Clin. Nutrition* Vol. 58, No. 5 (Nov. 1993), pp. 602-607.

FIGURES

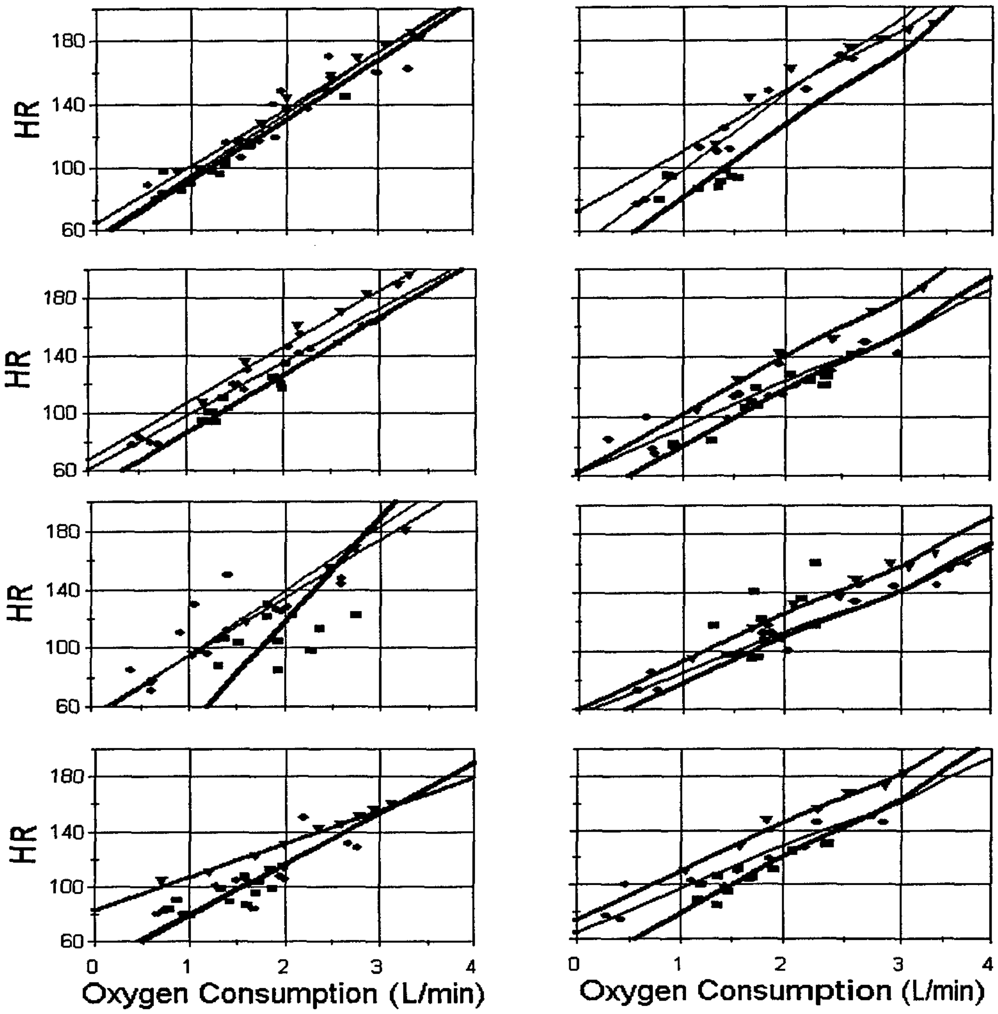


Figure 1. Figure 1: Heart rate as a function of absolute oxygen consumption ($\dot{V}O_2$) at steady state, all depths. Each panel contains data from one subject. ▼ and medium line = surface measurements breathing air, ■ and heavy line = immersed measurements breathing HeO_2, ● and thin line = dry chamber measurements at depth, breathing HeO_2. The lines are the regressions for all depths, pooled. For comparison with Table 4, subject 1 is the top left, subject 2 the top right, etc.

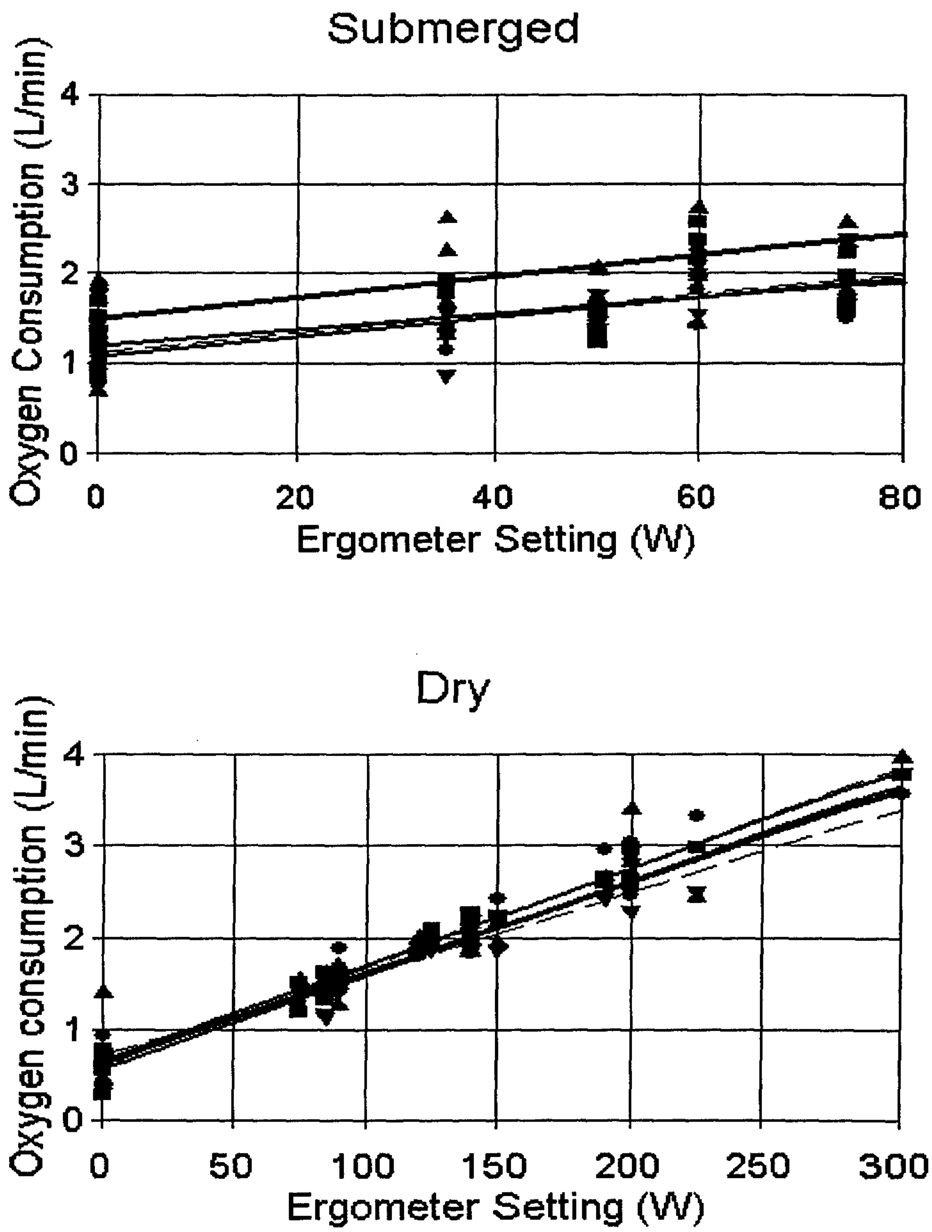
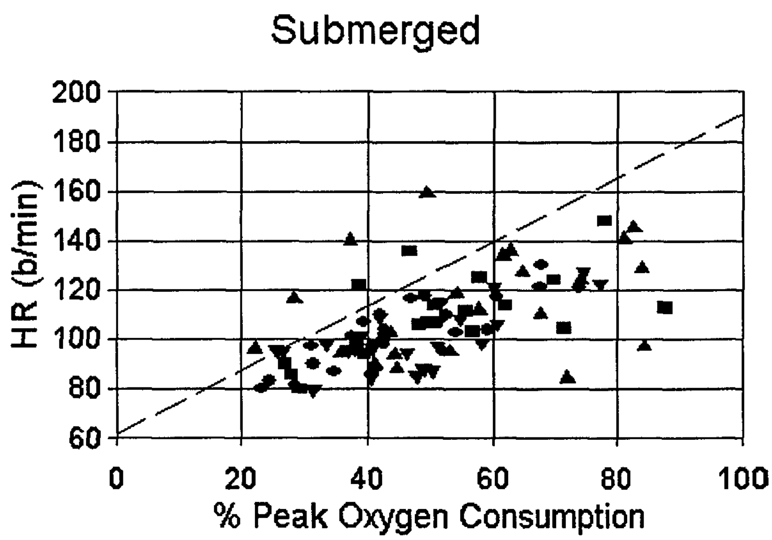


Figure 2: Oxygen consumption ($\dot{V}O_2$) as a function of ergometer workload — Submerged, and Dry. Each point represents a value from one subject, averaged over 15 minutes submerged or 1 minute dry. Lines are regressions at each depth. ■ and solid line = 33 fsw, ● and long dashed line = 66 fsw, ▼and medium dashed line = 190 fsw, and ▲and short dashed line = 300 fsw. Dashed line = surface (dry only).



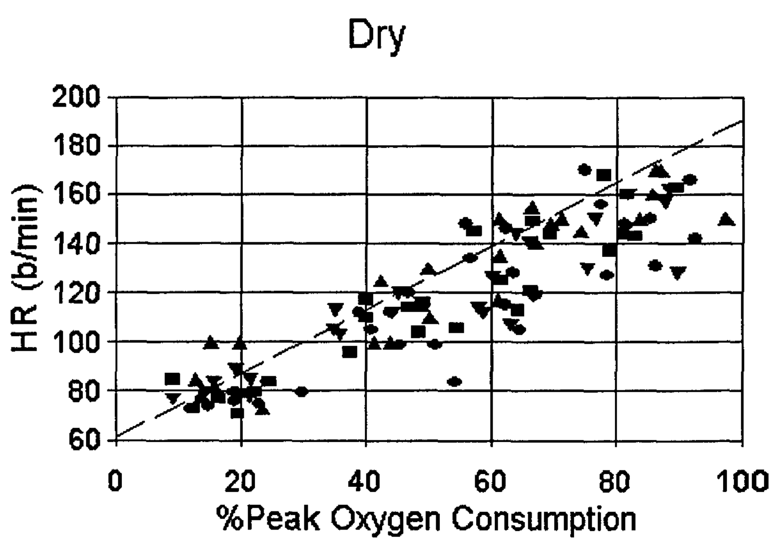


Figure 3: Heart rate as a function of percentage of maximum oxygen consumption (% $\dot{V}O_2$max) at steady state — a) Submerged, and b) Dry. Each point represents a single measurement of oxygen consumption and heart rate, d over 15 minutes submerged or 1 minute dry. ■ = 33 fsw, ● = 66 fsw, ▼ = 190 fsw, and ▲ = 300 fsw. Broken line = regression for surface (dry) data.

TABLES

Table 1: Diver characteristics

n = 8, male	Median	Minimum	Maximum
Age — years	30	28	44
Height — inches (cm)	71.5 (183)	66 (169)	73 (187)
Body mass —pounds (kg)	194 (88)	165 (75)	210 (95)
Maximum oxygen consumption (mL/(min·kg))	34	31	51

Table 2: Regression parameters for heart rate (HR) (beats/min) as a function of oxygen consumption ($\dot{V}O_2$)(L/min). Averages of regression parameters for individual subjects.

IMMERSED	HR vs. $\dot{V}O_2$								
Depth (fsw)	Slope	Min slope	Max slope	Incpt	Min Incpt	Max incpt	Median r^2	Min r^2	Max r^2
33	40	33	61	41	35	46	0.99	0.76	1.00
66	31	26	41	57	43	61	0.95	0.85	1.00
190	50	42	98	40	32	45	0.93	0.58	0.99
300	44	36	61	35	27	39	0.97	0.84	1.00
ALL	**39**	**33**	**45**	**43**	**29**	**51**	**0.68**	**0.17**	**0.92**
DRY									
surface	**36**	**34**	**38**	**68**	**59**	**72**	**0.98**	**0.92**	**0.99**
33	33	31	36	59	51	63	0.99	0.96	1
66	35	32	40	54	44	60	0.97	0.87	1
190	31	29	34	64	56	67	0.99	0.96	1
300	43	38	52	56	39	62	0.95	0.84	1
ALL HeO_2	**37**	**34**	**41**	**56**	**41**	**66**	**0.86**	**0.72**	**0.97**

Parameters were transformed from the regression of oxygen consumption on HR.

Min, Max are transformed parameter ± 1 standard error.

Incpt means intercept, and r^2 is squared correlation coefficient, the fraction of variance explained by the regression.

"All immersed", "surface" and "all HeO_2" are the averages of regression parameters for each subject with all depths pooled.

Table 3: Regression parameters for oxygen consumption ($\dot{V}O_2$)(L/min) as a function of ergometer setting (W). Averages of regression parameters for individual subjects.

IMMERSED	$\dot{V}O_2$ vs. work rate				
Depth (fsw)	Mean Slope	SE	Mean Intercept	SE	Median r^2
33	0.013	0.002	1.2	0.1	0.99
66	0.012	0.001	1.04	0.08	0.95
190	0.009	0.002	1.20	0.09	0.93
300	0.011	0.002	1.5^{+}	0.1	0.97
ALL	**0.011**	**0.002**	**1.2 ***	**0.1**	**0.95**
DRY					
Surface	**0.0092**	**0.0002**	**0.67**	**0.03**	**0.99**
33	0.0108	0.0004	0.59	0.04	0.98
66	0.0107	0.0005	0.64	0.05	1.00
190	0.0101	0.0004	0.58	0.06	1.00
300	0.009	0.001	0.7	0.1	0.98
ALL HeO_2	**0.010**	**0.001**	**0.63 ***	**0.07**	**0.98**

SE is standard error and r^2 is squared correlation coefficient, the fraction of variance explained by the regression.

* The probability $p < 0.001$that the pair comes from the same distribution.

$^{+}$ The probability $p < 0.02$ that the value is the same as those at the other depths.

Table 4: Fraction of variance explained by regression within each subject's data set, r^2, all depths pooled. Coefficients of variation for estimates of oxygen consumption from heart rate using the surface regression equation.

Subject number	Fraction of total variance explained by regression			Coefficients of variation for estimated oxygen consumption		
	Surface	Immersed	Dry	Surface*	Immersed	Dry
1	0.99	0.87	0.82	5%	24%	18%
2	0.92	0.17	0.97	10%	73%	19%
3	0.98	0.92	0.96	5%	36%	20%
4	0.99	0.90	0.86	4%	35%	31%
5	0.99	0.18	0.72	4%	42%	28%
6	0.98	0.27	0.96	5%	28%	23%
7	0.99	0.58	0.72	4%	72%	59%
8	0.98	0.78	0.87	5%	52%	36%

* The surface data were used both for fitting the prediction equation and to calculate the coefficient of variation. This double use reduced the estimate of the variation from the fitted curve from what could be expected with a different set of heart rates.

DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
321 BULLFINCH ROAD
PANAMA CITY, FLORIDA 32407-7015

IN REPLY REFER TO:
3905/01-19
Ser 02/**283**
14 Nov 02

From: Commanding Officer, Navy Experimental Diving Unit
To: Commander, Naval Sea Systems Command (00C3)

Subj: DEEP DIVE 2001

Ref: (a) COMNAVSEASYSCOM Task 01-19

Encl: (1) Barbara E. Shykoff and Marie E. Knafelc, *Exercise Heart Rate as a Predictor of Oxygen Consumption during Decompression from Saturation Diving*, NEDU TR 02-15, November 2002.

1. During the decompression phase of Deep Dive 2001 we studied the relation between exercise heart rate and oxygen consumption during in-water cycling and dry cycling in the chamber. Exercise studies were performed during holds at 300, 190, 66, and 33 feet of seawater (fsw), as well as on the surface before the dive. The results are presented in enclosure (1).

During submerged exercise, oxygen consumption was calculated from the MK 16 underwater breathing apparatus (UBA) bottle pressure drop, and during dry exercise, from collected expired gas. Oxygen consumption increased linearly with ergometer work, with the same slope submerged or dry, but the no-load intercept was higher submerged than dry. The work of moving the water while pedaling with no-load and of breathing on the UBA corresponded to 54±15 W.

Heart rate increased linearly with oxygen consumption. The slope was independent of depth or immersion, and the intercept was independent of depth. The median error in estimating oxygen consumption from heart rate was 12% on the surface, 23% submerged, and 31% in the dry chamber.

2. My point of contact is Barbara Shykoff at (850) 230-3134.

Patrick J. Keenan

P. J. KEENAN

Copy to:
CAPT Marie Knafelc